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A LATE PLEISTOCENE INTERTIDAL BOULDER PAVEMENT FROM AN ISOSTATICALLY EMERGENT COAST, DUNDALK BAY, EASTERN IRELAND

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ABSTRACT

Late Pleistocene sequences around Dundalk Bay, eastern Ireland, record glaciomarine sedimentation near the margin of a grounded ice lobe around 15 ka BP. A coastal exposure at Cooley Point consists of four major facies deposited outside this ice limit. (1) A basal mud facies deposited from sediment plumes accumulated following the initial ice marginal retreat inland. It contains a well-preserved Arctic microfauna dominated by the foram *Elphidium clavatum* and the ostracod *Roundstonia globulifera*. (2) A flat to undulating boulder facies (pavement), mostly one clast thick, is found pressed into the mud and is characterized by bevelled and striated upper clast surfaces. Pavement attributes are a result of intertidal activity in a cold climate. The boulder source is due to rafting by ice floes from glacigenic debris deposited during an ice advance. (3) Laminated sand facies drape the pavement and are a result of variable current activity. (4) The overlying gravel facies is separated from the sand facies by a marine erosion surface. The gravel facies is subaqueous, channelized and is overlain by late glacial raised beach ridges. Locally the gravels have been deformed by ice pressure from partially floating ice floes.

Facies changes record terrestrial submergence and provide evidence for changes in relative sea level during part of the last deglacial cycle. The boulder pavement and deformed gravel facies suggest that ice floes and sea ice effects may be more common within stratigraphies along emergent coasts than previously thought, though they have a low preservation potential. Extreme conditions during the deglacial favoured opportunistic microfaunas during mud deposition. This event may be related to a major meltwater event within the Irish Sea Basin.

KEY WORDS intertidal boulder bed; deglacial facies; glaciomarine microfaunas; sea level change

INTRODUCTION

Subhorizontal boulder beds (pavements) which are often one clast thick and striated on their upper surfaces have been associated with a range of processes operating in subglacial (Boulton, 1978; Clark, 1991), shallow water glaciomarine (Eyles, 1988) and cold climate intertidal environments (Dionne, 1981; Hansom, 1983, 1986; Eyles, 1994). Subglacial pavements are generally associated with glacial diamicts (Boulton, 1978; Clark, 1991; Hicock, 1991) while glaciomarine examples are often identified from stacked diamicts as lag concentrates abraded by ice shelves (Eyles, 1988, 1994). Factors involved in the formation of boulder pavements in cold-climate intertidal zones include boulder source, substrate, tidal range, degree of exposure and abrasion by mobile ice masses (Dionne, 1979, 1981; Martini, 1981; Taylor and McCann, 1983; Hansom, 1983, 1986; Eyles, 1994). The basis of pavement interpretations is their sequence context and relationships to subjacent sediments since similar morphological forms may develop in a range of environments.

The emergent western coastal margins of the Irish Sea Basin have undergone dramatic changes in land and sea configuration during the last deglacial cycle which are dependent on interaction between decaying ice

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sheet margins, isostatic and eustatic controls (Stephens and McCabe, 1977; Synge, 1977). Raised deglacial sequences therefore provide the potential to yield information on deglacial stratigraphy and shoreline structures formed in shallow water. The purpose of this paper is to describe an intertidal boulder pavement and associated facies exposed by marine erosion at Cooley Point on the north shore of Dundalk Bay (Figure 1). The boulder pavement is part of a largely submergent facies sequence which is overlain by a late glacial raised beach and provides an improved record of sea level changes during part of the last deglacial event.

Although intertidal boulder pavements should be found primarily on isostatically emergent coasts, their preservation potential is often low (Hansom, 1986). This is due to erosion during both transgressional and regressional spikes. For example, in northwest Britain, laterally extensive (1–2 km) surfaces of marine erosion occur between the deglacial sediments and overlying raised beachface gravels. Occasionally shallow water, wave-influenced sand/mud facies provide a more complete sedimentary record (McCabe *et al.*, 1994). The Cooley Point sequence records the transition from open glaciomarine to intertidal conditions prior to an advance of the ice margin, deposition of subaqueous outwash and the maximum of the late glacial transgression.

REGIONAL SETTING AND ICE FLOW

Dundalk Bay is an eastward extension of the Irish lowlands situated on the western margin of the Irish Sea Basin (Figures 1A, 1B). Low lying topography (<30 m a.s.l.) bordering Dundalk and Carlingford bays is developed on Silurian shales and greywackes with faulted outliers of Carboniferous limestone (Holland, 1981). The higher ground of the Carlingford and Mourne Mountains consists of Tertiary igneous intrusions (Figure 1C).

Deglaciation of the northern Irish Sea Basin occurred around 15 ka BP (Bowen *et al.*, 1986) and was marked by phases of ice stabilization and advance during tidewater recession (Stephens and McCabe, 1977; Eyles and McCabe, 1989). The resulting morainic ridges bordering the bays are composed of

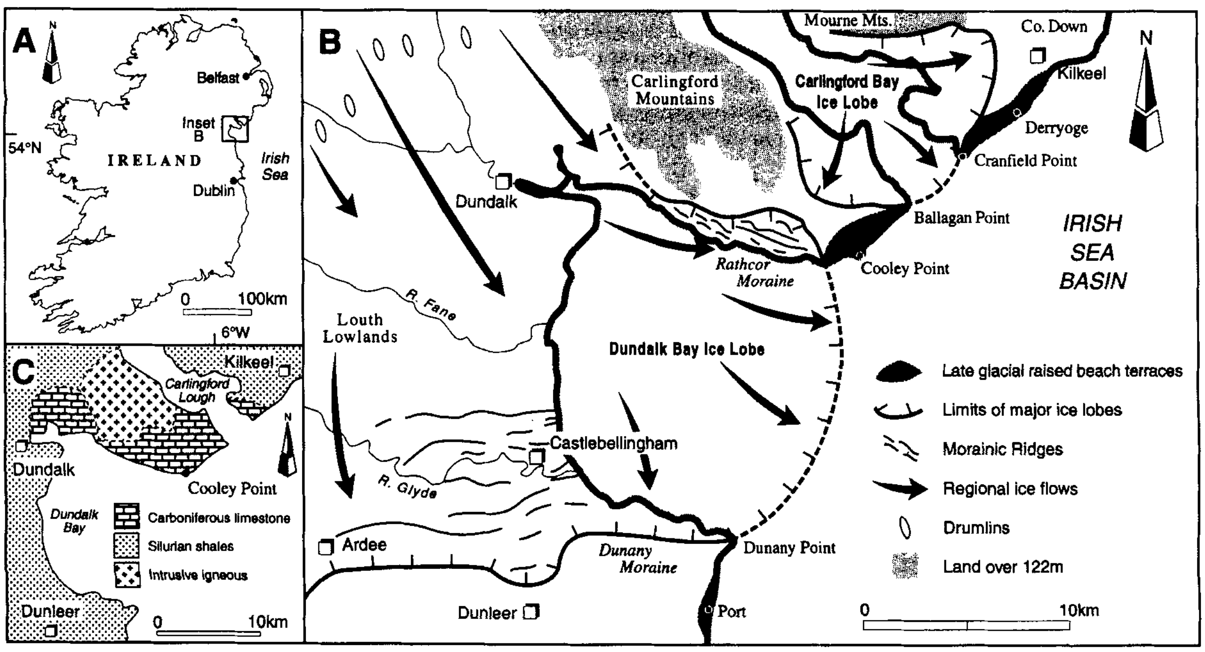

Figure 1. (A) Location of study area in Ireland; (B) ice flow directions, ice limits and sites mentioned in text; (C) local geology around Dundalk Bay

interbedded diamicts, muds, sands and gravels which record shallow glaciomarine sedimentation and ice thrusting along the margins of grounded ice lobes (Figures 1B, 2) (McCabe *et al.*, 1987). Erratic and directional indicators show that the ice marginal sequences are associated with major debris and meltwater fluxes southeastwards during drumlinization of the lowlands (Dardis and McCabe, 1983).

Well-defined, late glacial raised beach systems occur only in deglacierized areas outside the limits of the Dundalk Bay ice lobe (Figure 1B). This relationship indicates that the ice lobes in Dundalk and Carlingford bays were largely contemporaneous and persisted during the maximum of the late glacial transgression. The facies sequence at Cooley Point (Figure 3) is located 1·8 km east of the push moraine at Rathcor and occurs directly beneath an extensive late glacial beach complex at Templetown (Figure 2). The Cooley Point sediments therefore predate the raised beach complex but post-date the initial deglaciation of the outer bay (Figures 1B, 2).

FACIES DESCRIPTION

The Cooley Point exposure was examined with regard to sediment-body geometry, stratigraphy, facies types, texture, clast shape, primary sedimentary structures (Figure 3) and faunal content. The resulting data were used to identify four major facies (mud, boulder, sand and gravel) (Figure 3). Measurements from 36 clasts from the boulder facies were taken after washing clast surfaces (Table I). Although clast selection depended to a degree on the amount of scree, measurements were taken on clasts at intervals of less than 5 m.

Mud facies

This facies is up to 1·5 m thick above the present beach and consists mainly of massive to horizontally laminated mud (Figure 3). In the eastern part of the section the mud is interbedded with steeply dipping (< 60°) and contorted sandy laminae immediately below the boulder facies (Figure 4A). The variable laminated mud contains numerous wispy sand stringers (<0·5 cm thick) and occasional small pebbles (<1 cm).

The muds contain a rich microfauna dominated (99 per cent) by the foram *Elphidium clavatum* (84 per cent) and the ostracod *Roundstonia globulifera* (15 per cent). Forty per cent of the forams are well-preserved

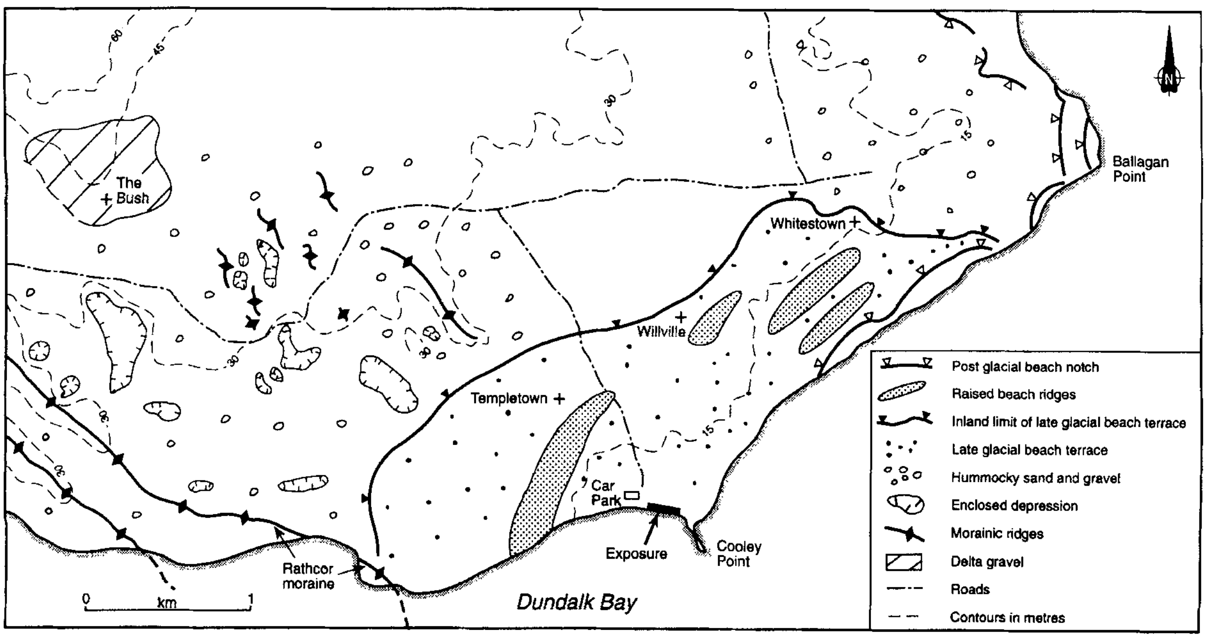

Figure 2. Location of critical sites, ice limits and raised marine features on the north shore of Dundalk Bay

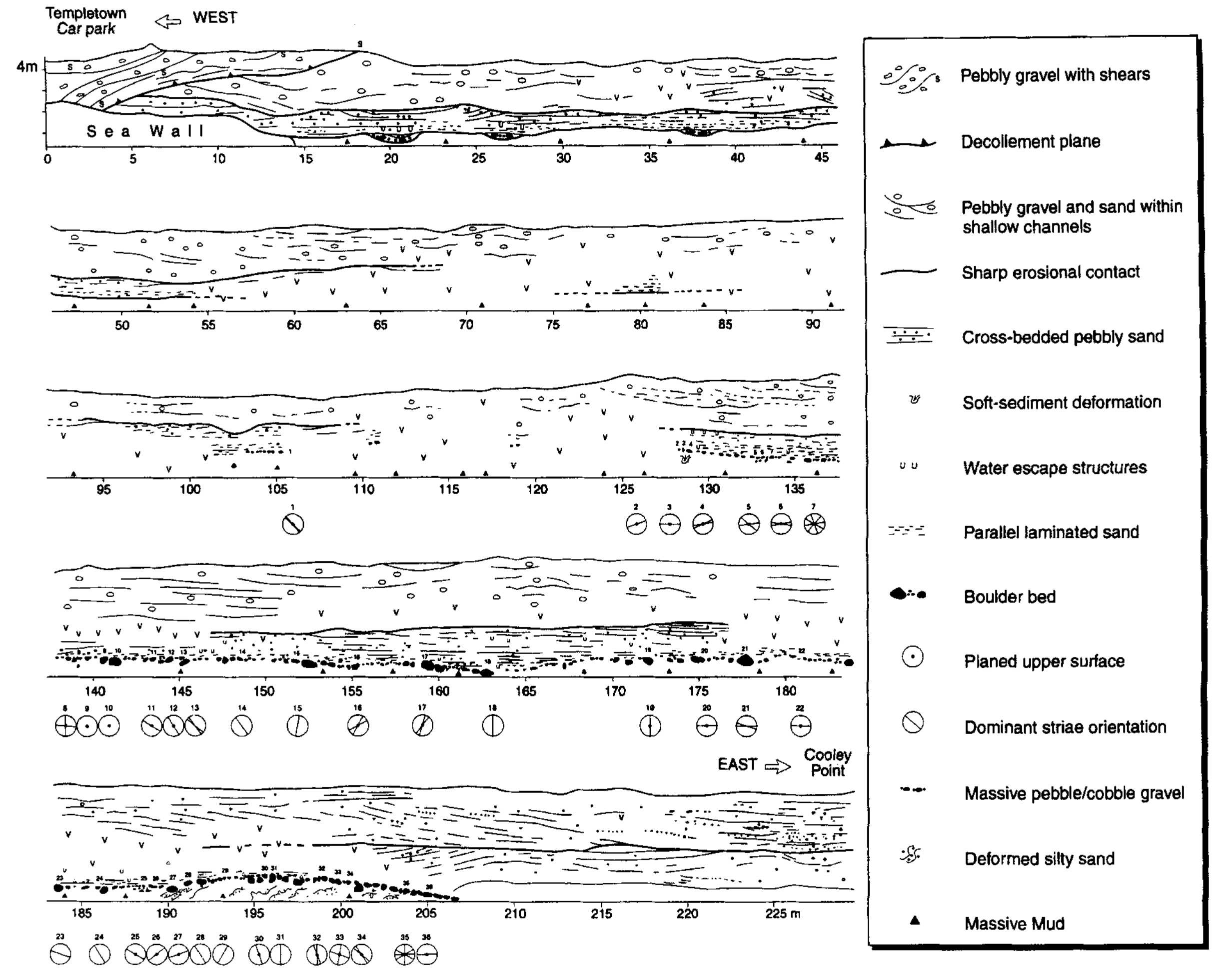

Figure 3. Spatial relationship of lithofacies exposed at Cooley Point and striae orientations on upper clast surfaces of the boulder bed

with intact apertural faces and the majority of the rest are lustrous and transparent with broken apertural faces. Ninety-one per cent of the ostracods have both valves preserved. The microfauna from the contorted sands is poorly represented with only broken, opaque specimens of *Elphidium clavatum*. Monospecific samples of *Elphidium clavatum* provide AMS ^{14}C dates of 14 980 ± 110 (AA 17 693), 15 350 ± 110 (AA 17 694) and 15 380 ± 140 (AA 17 695).

Boulder facies

This facies is mainly (70 per cent) a bed of single clasts with local concentrations of near-touching to wedged clasts (Figures 3, 4). At the eastern end of the exposure the boulders form a pavement which continues below the eroded cliffline (Figure 5). Surface undulations in the bed are up to 10 m across by 1 m in depth (Figure 4A). Individual boulders (75 per cent) are embedded in mud and separated by mud wedges at least 10 cm thick (Figure 4B). The remainder (25 per cent) are less than 10 cm apart with touching edges.

Clast characteristics are shown in Table I. Clasts are mainly Carboniferous limestone (79 per cent) and range from small cobbles (13 cm) to medium boulders (1 m). The largest boulders tend to occur where the bed is one clast thick and cobbles are most common within clusters (1·3 m across by 0·6 m deep) which contain up to 12 clasts (Figure 4C).

Table I. Clast characteristics from the boulder bed, Cooley Point

Number of clasts	Lithology (%)			Size (cm)						Shape (%)				Packing characteristics					Dip of a-axes			Glacigenic characteristics (%)			
				Mean		Smallest		Largest						(%)		(cm)		(%)							
	Carboniferous Limestone	Silurian Grits	Granites	a-axis	b-axes	a-axes	b-axes	a-axes	b-axes	Faceted	Edge rounded	Bullet	Angular	Wedged	Single	>10 cm to adjacent stone	<10 cm to adjacent stone	Pressed into mud	Flat, <10°	Inclined, 10–45°	Steep, 45–90°	Planar upper surface	Striated upper surface	Two or more sides faceted	Striated on more than one facet
36	79	18	3	43	25	18	14	113	60	53	31	11	5	30	70	75	25	100	91	3	6	73	96	75	73

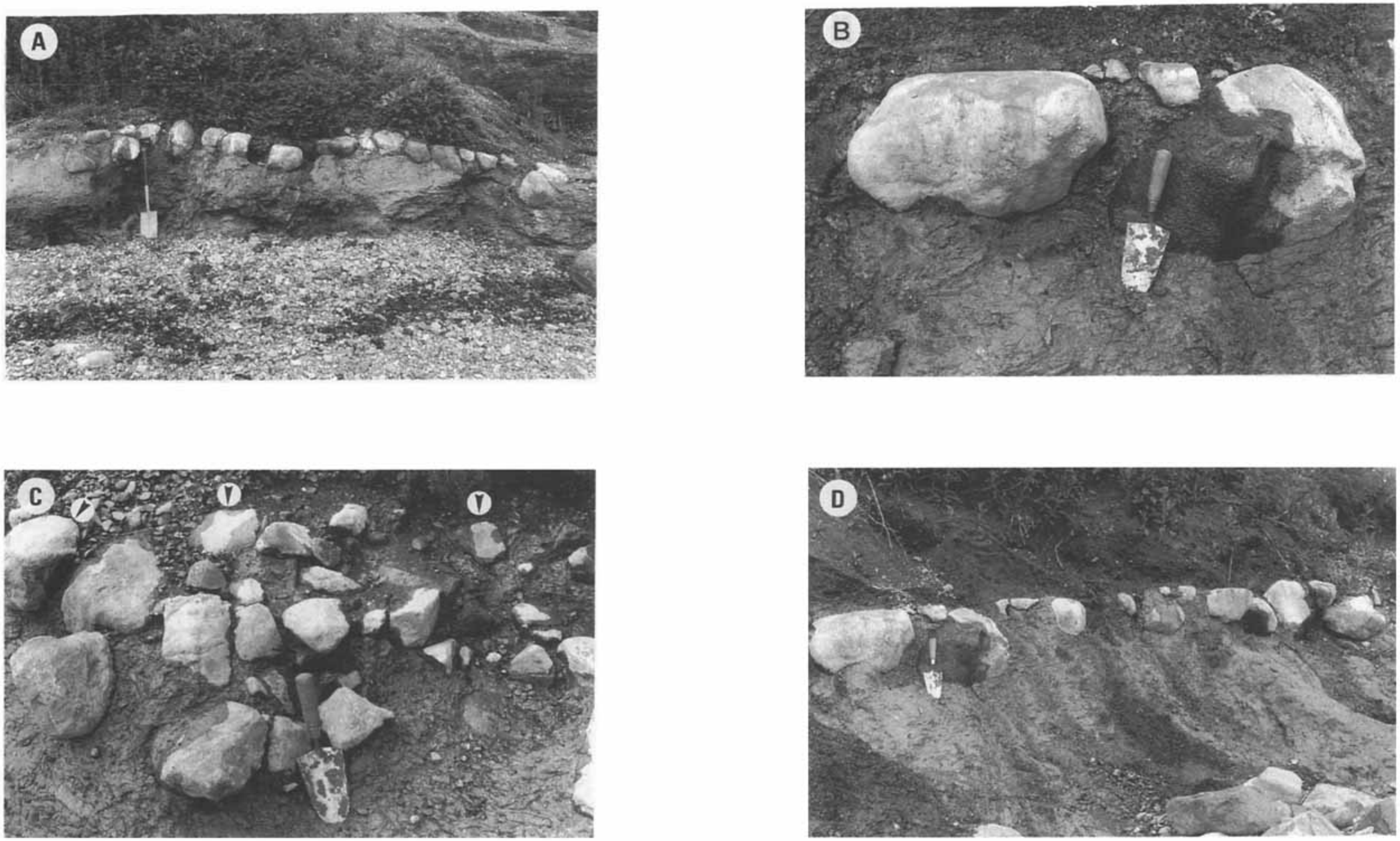

Figure 4. Sedimentary characteristics of the intertidal boulder bed and its relationships to subjacent facies, Cooley Point, Ireland. (A) Shallow undulations along the surface of the boulder bed. Note the bevelled, upper clast surfaces and contorted laminae to right of spade. Spade is 1 m long. (B) Detail of relationship between the mud facies and ice-pressed boulders. Note the presence of 'mud pillars' between the clasts and the bevelled, upper clast surfaces. Trowel is 30 cm long. (C) Isolated boulder cluster along the top of the platform. Note that the platform surface is flat-lying (arrowed) and that boulder edges are in many cases touching. Contorted mud infills irregularities between clasts. Trowel is 30 cm long. (D) Well-developed, flat-lying bevelled surface of the boulder bed which is related to the ice-saw action of shore ice. Trowel is 30 cm long

Figure 5. Mosaic-like packing of boulders into mud facies, along the bevelled pavement surface, Cooley Point. The pavement surface is well-exposed at the eastern part of the section and continues below overlying sand and gravel facies. Spade is 1 m long

The vast majority (91 per cent) of clast *a*-axes are flat-lying (<10°). Those (6 per cent) with steeply-dipping (<45°) *a*-axes occur mainly within clast clusters (Figure 4C). The upper surface of most (73 per cent) clasts are strongly bevelled and form a prominent pavement surface (Figure 4D). A majority (96 per cent) of these polished upper surfaces show striae which vary from discontinuous scratches to parallel and cross-cutting lineations. About 50 per cent of clast surfaces contain more than one distinct set of striae and dominant striae do not show a unidirectional trend. Comparisons between dominant striae orientation and clast *a*-axis orientations, either on individual clasts or on a collective basis, do not show any simple relationship (Figure 6).

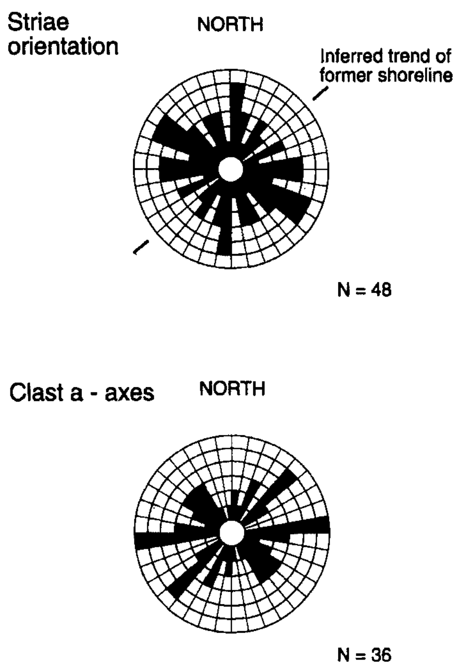

Figure 6. Rose diagrams showing striae orientation from upper clast surfaces in the boulder bed and orientation of clast *a*-axes along the boulder bed. Orientations of individual clasts are shown in Figure 3

Along the western part of the exposure the boulder bed can be traced laterally into a sharp, planar junction separating the mud and sand facies (Figure 7). At three locations, immediately below the junction, lenses of gravelly debris (<4 m across by 0·3 m deep) occur in the same stratigraphic position as the boulder bed (Figure 8). The upper surfaces of the lenses are planar and the lower contacts with the mud are sharp and concave. Typically, these structures are infilled with cobble gravel which is massive and variably matrix-supported and clast-supported. Clasts are edge to subrounded. At two sites, cobble cluster forms show a strong westerly imbrication of the *ab* axes.

Sand facies

This facies is tabular (2–3 m thick) and rests on the unweathered surface of the boulder pavement and mud (Figures 3, 7). Up to 10 cm of rhythmically bedded, laminated silty sand delicately drapes irregularities on the pavement surface (Figure 9). Upwards the sequence coarsens conformably into parallel laminated medium sand (1–2 m thick) and pebbly sand (~2 m thick). Laminae are well sorted, variable in thickness (0·25–1·0 cm), massive or normally graded, laterally continuous (<15 m) and contain mud rip-up clasts (Figure 7). Occasional rippled beds resembling linsen structures (De Raaf *et al.*, 1977) indicate a palaeoflow towards 100°. At intervals the horizontal lamination is broken by curving-upward sets of laminae and convolutions which are abruptly truncated by flat-lying laminae. The upper part of the sequence shows low angle (<5°), cross-bedded pebbly sands characterized by shallow scours, pebble lags, dispersed pebbles, mud rip-up clasts and frequent textural changes.

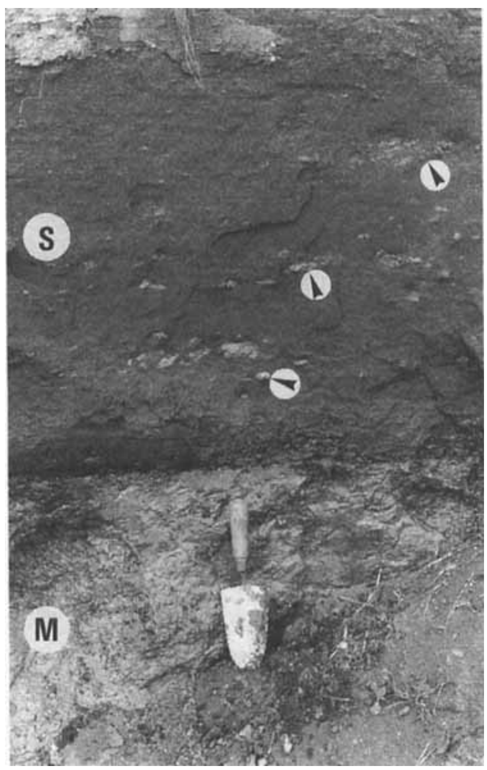

Figure 7. Planar contact between mud (M) and sand (S) facies, Cooley Point. Note the presence of numerous mud clasts (arrowed) within the parallel laminated sand. Laterally this planar contact can be traced into the boulder bed. Trowel is 30 cm long

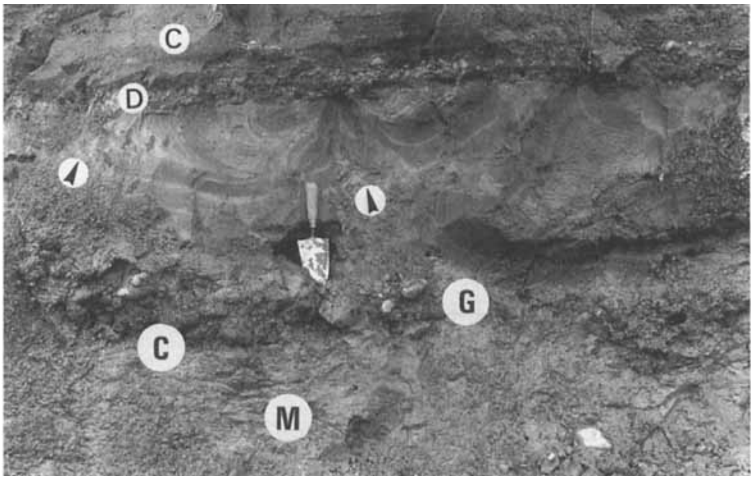

Figure 8. Lens of massive cobble gravel (G) overlying mud facies (M), Cooley Point. The base of the gravel lens is sharp and concave (C). The sand unit above the gravel is contorted and shows dish and pillar structures (arrowed) associated wth water escape. Note that the laminations of the contorted unit are truncated and overlain by a thin bed of pebbly debris (D) and parallel laminated sand (S). Trowel is 30 cm long

Gravel facies

The sand facies is truncated by a sharp planar to undulating erosion surface (Figure 3). Overlying pebbly gravel infills multiple, cross-cutting scour features which range from 10 to 30 m across by a few metres in depth. Stratification is recorded by coarse pebble lags, cobble lags, frequent and abrupt textural changes and diffusely laminated sandy beds. Most beds (70 per cent) are massive, poorly sorted and matrix-supported (Figure 10). Amalgamated junctions are common. Less frequent (20 per cent) lithofacies consist of better-sorted, planar cross-bedded gravels and occasional beds of openwork cobble gravel together with bimodal

Figure 9. Detail of flat, draped lamination across the bevelled surface of the boulder pavement, Cooley Point. The presence of small scale convoluted laminae (arrowed) at the base of the drape structure is associated with fluidization and water escape. Trowel is 30 cm long

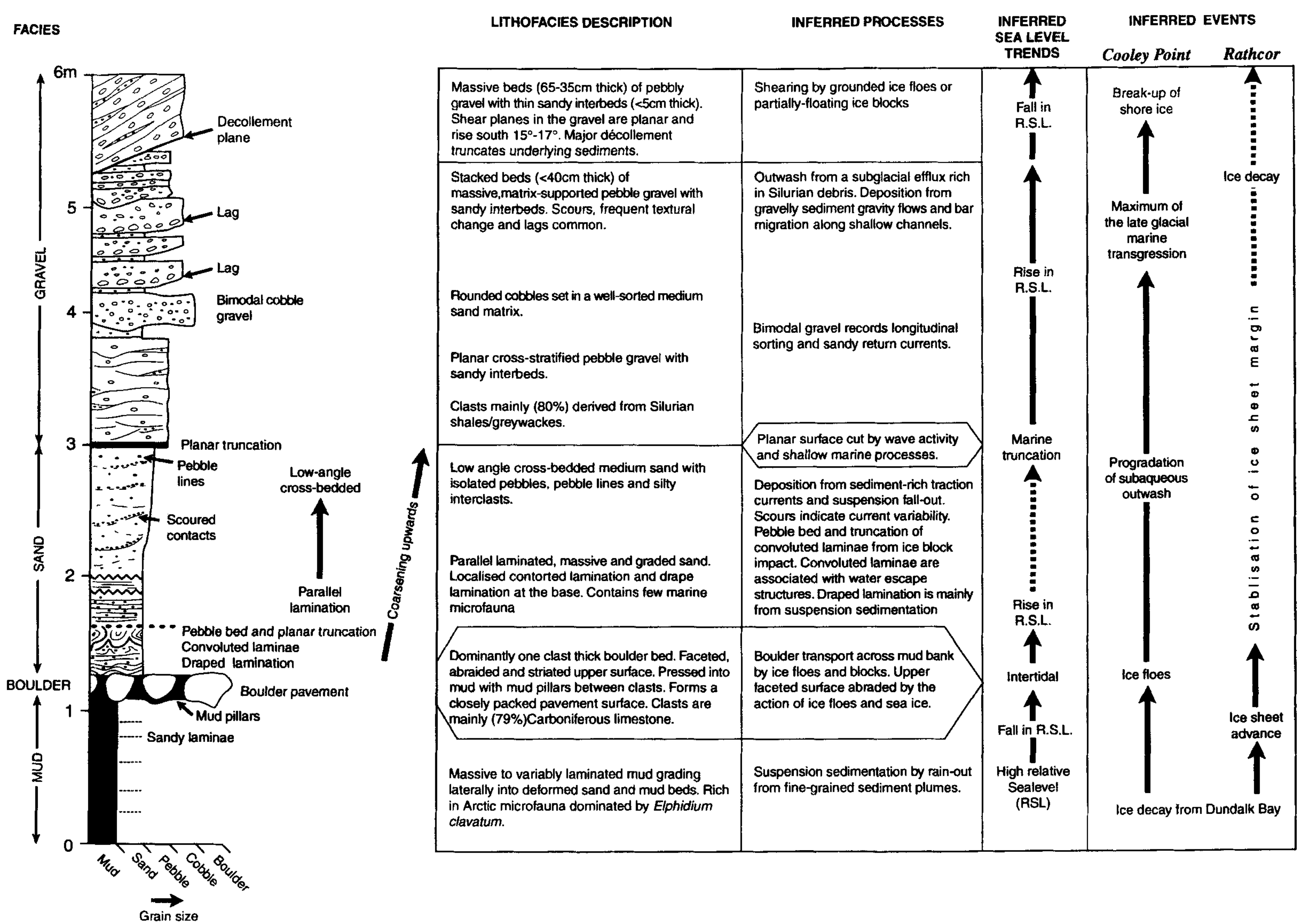

Figure 10. Measured log from Cooley Point summarizing the main sedimentary structures in the mud, boulder, sand and gravel facies, the contact relationships and inferred processes, sea level trends and events

cobble gravel (cobbles set in a well-sorted sand matrix) (Figure 11 A,B). These lithofacies consist mainly (80 per cent) of Silurian shales and greywackes.

At the western end of the exposure a well-defined décollement truncates both the mud and gravel facies and rises eastwards at 15° to 17° (Figure 3). Above the décollement plane both gravelly beds and pebble-sized clasts are aligned subparallel with sets of nested shear planes.

FACIES INTERPRETATION

Mud facies

The mud facies is part of a regional mud drape along the northern shore of Dundalk Bay (McCabe *et al.*, 1987). Ice thrust, prograded gravelly efflux sequences overlie the mud and record the last ice advance in Dundalk Bay to Rathcor (Figures 1, 2). The largely clast-free mud therefore records pelagic sedimentation

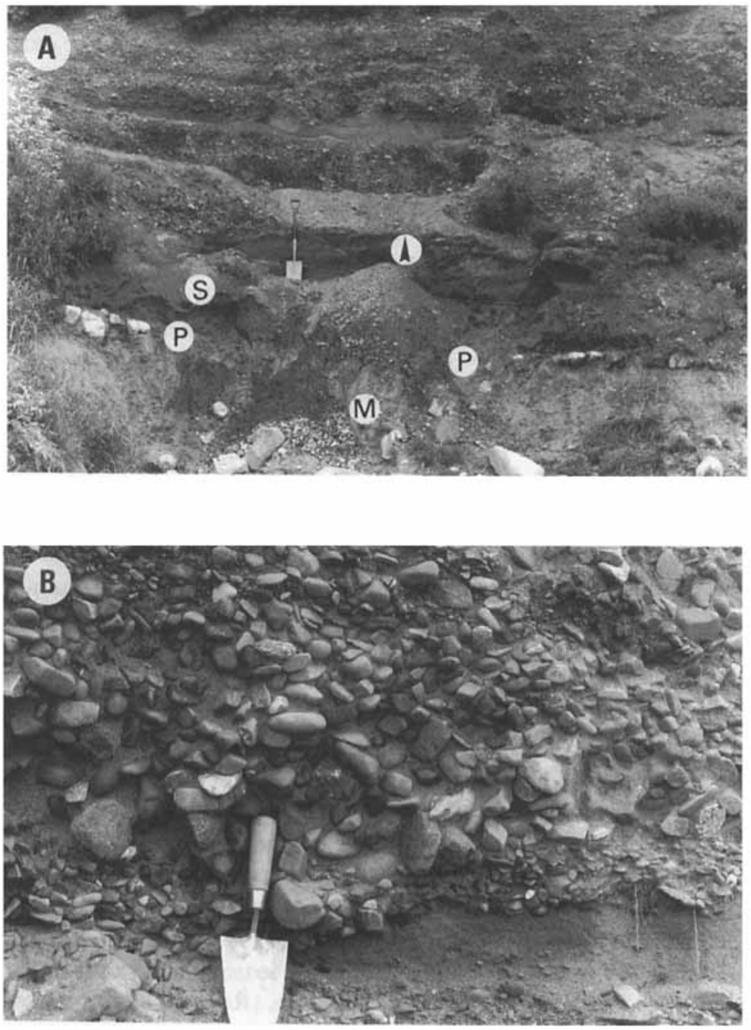

Figure 11. Structures from the gravel facies, Cooley Point. (A) Stacked and amalgamated beds of massive pebble to cobble gravel with isolated cobble clasts within shallow scour features. The base of the gravel facies is sharp and planar (arrowed). Underlying facies are sand (S), boulder (P) and mud (M). Spade is 1 m long. (B) Massive bed of bimodal gravel, cobbles are edge- to subrounded and occur within a well-sorted sandy matrix. Trowel is 30 cm long

during a low energy, ice-free phase prior to the Rathcor advance, with no extensive ice rafting (cf. Powell, 1981, 1983, 1990) (Figure 10).

The well-preserved Arctic microfauna, dominated by opportunistic species, is typical of harsh glaciomarine environments (0·5–2·5°C, turbid, low salinities). Similar biofacies assemblages have been identified from contemporary Arctic and subarctic areas vacated by tidewater glaciers (Nagy, 1965; Hald *et al.*, 1994; Jennings and Helgadottir, 1994).

Boulder facies

In some cases the origins of boulder pavements are uncertain because their stratigraphic context is in doubt or there is inconclusive evidence on the type of ice mass involved in pavement development. The development of the example from Cooley Point can be evaluated from three types of field evidence (Figures 10, 12):

1. Ice limits/stratigraphic position. The boulder pavement occurs 1·8 km outside the Rathcor moraine and is not associated with glacigenic diamicts. It is underlain by open-water muds which predate the Rathcor moraine and overlain by draped lamination. The sequence context arguments therefore show that the pavement is not associated with subglacial structures. It is more likely to have developed in a very shallow water, deglacierized area (Figure 12).

2. Boulder source/sea level fall. Boulders resting on a clast-free mud cannot be derived by winnowing of the substrate. The absence of gravelly lags near the mud surface also rules out deposition from icebergs and subsequent winnowing. The high percentages of glacially faceted and bullet-shaped clasts are clearly of subglacial origin (e.g. Boulton, 1978) and the most probable source is the Rathcor moraine (Figure 2). Boulder transport to Cooley Point is possible by two mechanisms. First, iceberg rafting could have occurred as the ice margin advanced to and stabilized at Rathcor. However, ice rafting would probably have dispersed a variable clast population rather than cobbles and boulders. Second, boulder transport is more likely to result from winter ice followed by ice breakup and movement by mobile ice floes or refloated grounded ice blocks across the mud bank. Rosen (1979) and McCann *et al.* (1981), among others, have described how downward freezing of intertidal ice encases boulders as the ice cover is alternately raised and grounded on subarctic tidal flats. Observations from contemporary, boulder-strewn intertidal flats emphasize not only the role of wind- and current-driven ice floes in boulder transport but their rearrangement across the flats (Lauriol and Gray, 1980; Dionne, 1981; Guilcher, 1981; Hansom, 1983, 1986).

The inferred fall in relative sea level (r.s.l.) of about 30 m (glaciomarine highstand to pavement level) immediately prior to pavement formation is supported by both faunal and stratigraphic evidence. An abrupt change in biofacies between the well-preserved open-water Arctic assemblage of the mud below the boulder bed, and the poorly preserved (derived) specimens in the overlying drape lamination indicates a marked decrease in water depth. Stratigraphically this shallowing trend is mirrored by the facies change from mud to sand (Figure 12).

The tidal range is generally accepted to be an important variable in boulder dispersion and clast reorganization (Rosen, 1979; McCann *et al.*, 1981; Hansom, 1983). Tanner (1939) observed that boulder pavements from the fjords of the Barents Sea and in Labrador were best developed with tidal ranges of 2 to 4 m. If the late glacial tidal range in Dundalk Bay is similar to that at present (~4·5 m) it provides a crude comparison with the tidal ranges where contemporary boulder pavements develop.

3. Pavement characteristics. The planar top of the boulder bed, the paucity of upright or projecting clasts and deformed mud pillars between clasts suggest that the boulders were pressed into the mud (Figures 4B, 12). It could be argued that the presence of clast clusters and superimposed clasts record clast ploughing and glacier sliding over a deformable bed (e.g. Clark and Hansel, 1989). However, modern analogues show that multiple ice floes across bouldery tidal flats during successive seasons can result in highly variable boulder concentrations (Rosen, 1979). The latter tend to trap ice-cakes (Rosen, 1979) during subsequent breakups generally around low water level. Pavement undulations are also similar in cross-sectional scale to the 'polygonal depressions' recording stranded and rotating ice blocks in the subantarctic (Hansom, 1983; Eyles, 1994).

The mosaic-like packing of the boulders and striae variability along the boulder bed are also similar to

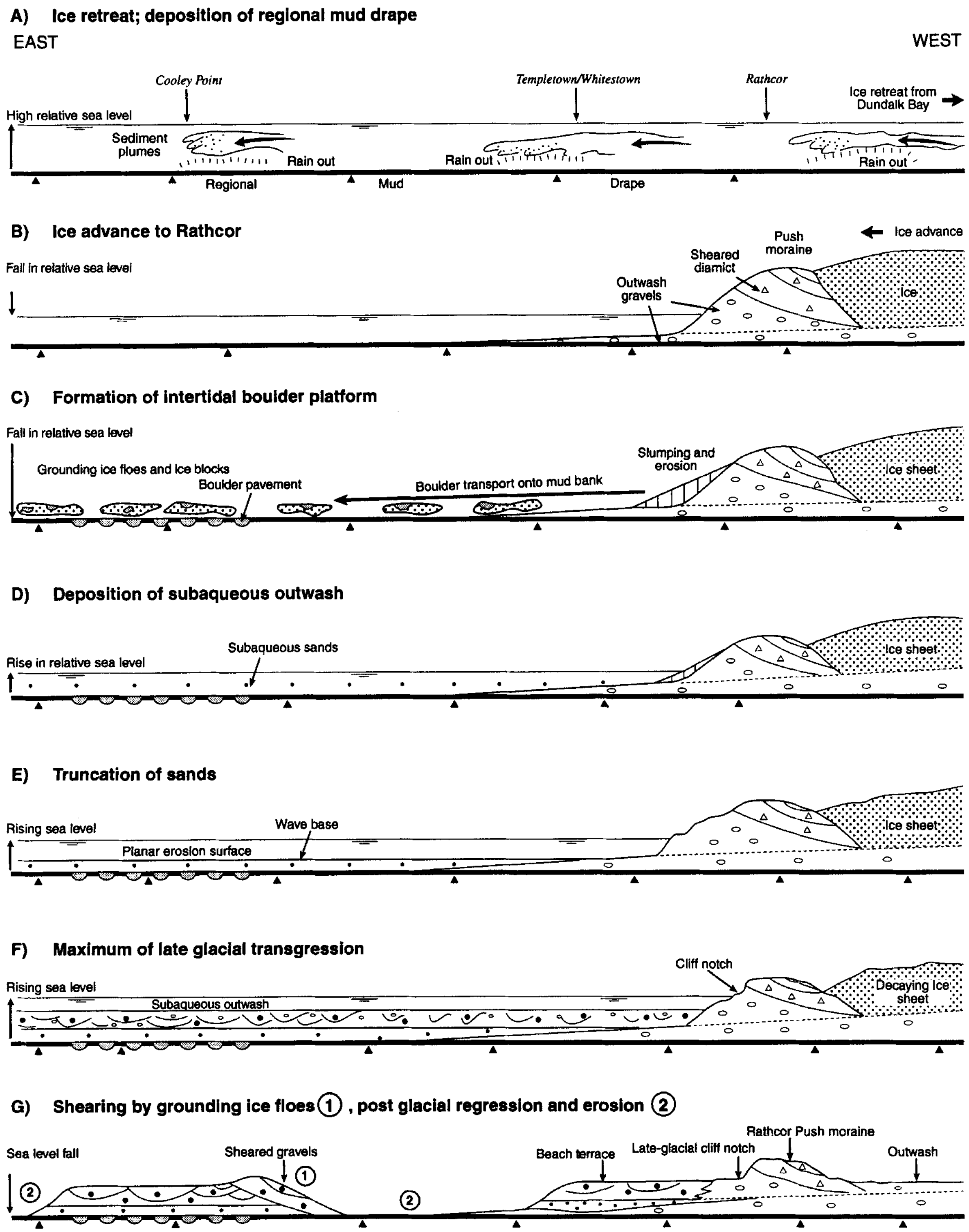

Figure 12. Cartoons illustrating the origins of the main stratigraphic elements present at Cooley Point and late glacial evolution along the north shore of Dundalk Bay, Ireland

pavements described from subarctic intertidal settings (e.g. Hansom, 1983, 1986). Clast reorganization is generally attributed to a combination of intertidal processes including sorting, stranding, pushing, pressing, dragging, rocking and mutual interference between adjacent clasts (Araya and Hervé, 1972; Mackay and Mackay, 1977; Dionne, 1981; Martini, 1981; Hansom, 1983, 1986).

Faceted and striated upper clast surfaces on the pavement surface closely resemble those produced by ice abrasion on clasts that were at least partially anchored in the substrate (cf. Mackay and Mackay, 1977; Martini, 1981). Striae variability, cross-cutting scratches and the absence of well-defined sets of subparallel striae on upper clast surfaces suggest that abrasion was effected by a see-saw action typical of that produced by the frequent action of freely moving ice floes (e.g. Hansom, 1983).

It is difficult to identify the margin of the contemporary shoreline during boulder pavement formation. This feature was probably aligned from southwest to northeast, subparallel to the late glacial beach ridges between the Rathcor and Ballagan Point moraines (Figure 2). If this is correct then about 70 per cent of the striae on upper clast surfaces occurred at high angles to the former shoreline trend (Figure 6). A similar relationship is typically produced by the onshore movement of floating ice or the rotating movement of tidally stranded ice blocks (Hansom, 1983).

The main factors which contributed to intertidal boulder pavement development at Cooley Point include: (a) a fall in r.s.l. from a glaciomarine highstand recorded by a marked change in biofacies below and above the boulder pavement; (b) a subglacial boulder source at Rathcor; (c) a mesotidal range facilitating free ice movement in near-shore zones; (d) the ice-dominated coastal environment with seasonal dynamic break-ups—resulting ice floes and refloated ice blocks effected boulder transport; (e) vertical ice pressures and ice abrasion by freely moving ice floes or blocks which reorganized the boulders into a pavement.

Sand facies

The horizontally bedded sands are typical products of sand-rich currents of varying velocity (Shaw, 1975). Upward transition into cross-bedded, pebbly sands within scour features marks an increase in current velocity. Disrupted silty laminae with upward-curving laminae are similar to water escape structures and may be generated by a range of processes (Lowe and LoPiccolo, 1974; Postma, 1983). However, where these intraformational dish and pillar structures are truncated locally by a planar surface and are overlain by horizontal laminae the increase in local pressures necessary for pore water migration and sediment deformation may have been generated by the erosive action of flat slabs of stranded ice. This interpretation is supported by the presence of pebbly debris immediately above the truncation plane which may record loading and melting of debris contained in the ice (Figure 8).

Sandy drapes immediately above the boulder bed and overlying massive and graded horizontal beds are rhythmically bedded and resemble turbidites. Similar facies have been recorded from shallow water settings (Gustavson and Ashley, 1975). However, this sand facies occurs towards the base of glaciomarine deltaic foresets to the west at Rathcor (McCabe *et al.*, 1987). The sands are therefore related to a rise in r.s.l. rather than the development of local topographic thresholds ponding water on the platform surface (Figure 12). Whether or not this rise in r.s.l. is related directly to renewed isostatic depression during the ice advance to Rathcor is not known.

Gravel facies

The sharp contact between the sand and gravel facies is well-marked along the exposure (Figures 3, 10). Stratigraphically this erosion surface is similar to wave-cut, transgressional surfaces and lags which occur below raised late glacial beachface gravels in Northern Ireland (McCabe *et al.*, 1994). Winnowing of the sandy facies at Cooley Point would not produce typical lag features.

Three interbedded gravel facies are contained within cross-cutting channels and are interpreted as subaqueous outwash (cf. Rust, 1977). Planar, cross-bedded sands and gravels are thought to be the product of bar migration along shallow channels, while matrix-rich, massive gravels formed by sediment gravity flow (Lowe, 1979; Nemec and Steel, 1984). The juxtaposition of massive gravel and better-sorted, graded gravel facies can be rationalized by downslope evolution in flow support mechanisms (e.g. Postma, 1984, 1985). Occasional beds of bimodal gravel may record longitudinal sorting of cobbles to a brink point together

with suspension deposition of sand from return currents (Iseya and Ikeda, 1987; Shaw and Gorrell, 1991).

Variability in texture and sedimentary structures in the gravel facies are similar to marine outwash deposits described by Powell (1990) from an incipient grounding line fan. The thick, amalgamated poorly sorted beds together with prominent scour surfaces also reflect wide flow energy fluctuations and pulsating discharge (e.g. Powell, 1990; McCabe and O'Cofaigh, 1995).

The subaqueous outwash is mainly (80 per cent) derived from Silurian bedrock whereas the intertidal boulder bed consists mainly (79 per cent) of Carboniferous limestone. The most probable debris source for the outwash would be a subglacial efflux located immediately to the south of Cooley Point along the frontal margin of the Dundalk Bay ice lobe (Figure 1B). This palaeoflow direction agrees with the south to north trend in channel axes.

At the western end of the section the décollement plane and associated shear structures in the gravels are not associated with glacigenic diamict (Figure 3). Their overall geometry is in sympathy and indicates ice thrusting from west to east (Figure 3), well to the east of the ice limit at Rathcor (Figure 2). These shear structures probably record either iceberg impact or sea ice activity. Contemporary observations show that shearing on this scale is well within the compass of large ice floes in shallow water which are capable of bulldozing and deforming beach sediment into ridges 12 m in height (e.g. Leffingwell, 1919; Nichols, 1961; Reimnitz *et al.*, 1972; Taylor and McCann, 1983). The late glacial beach terrace which post-dates and occurs inland from the Cooley Point sequence (Figure 2) implies a minimum water depth of 20 m during progradation of the outwash (Synge, 1977).

DISCUSSION AND IMPLICATIONS

At Cooley Point the facies sequence (open-water muds → intertidal platform → subaqueous outwash) records ice withdrawal from the bay followed by an easterly ice advance to the Rathcor ice limit (Figure 10). The late glacial raised beach gravels which overlie this sequence do not occur within the ice limits defined by the Rathcor moraine (McCabe, 1973). Therefore the successive morphological and sedimentological changes around the margins of Dundalk Bay are related to processes driven by changes in r.s.l. and the position of the ice margin (Figure 12).

Theory predicts that deglacial facies sequences in isostatically depressed basins should contain elements associated with submergence and emergence (Boulton, 1990). In the western Irish Sea Basin the typical deglacial sequence consists of glacigenic or glaciomarine diamict separated from overlying late glacial beach-face gravels by a marked unconformity (Stephens and McCabe, 1977). Stratigraphic evidence from Cooley Point records changes (~30 m) in r.s.l. following the initial deglaciation but predating truncation during beach formation. It is also evident that this facies sequence is only a partial record of possible process interactions. For example, shallow marine, wave-influenced sand facies are not present at Cooley Point. Regional sea level change therefore cannot be fully evaluated from 'end-marker' morphological evidence (e.g. raised beach) alone, as a significant part of the sea level record is contained within sequences which have a low preservation potential.

A major implication of the onshore record described here is that palaeoenvironmental changes were frequent (and rapid?) during the last deglacial cycle. Although this record is not typical for all ice marginal settings in the Irish Sea Basin, it does stress the need for more accurate records of the stratigraphic architecture of glacigenic and ice marginal facies that evolved close to retreating tidewater glaciers. The glacigenic and proglacial stratigraphic units identified by Eyles and McCabe (1989) from the basin are often interbedded and record process continua within or transitions between closely related palaeoenvironments. The evidence which has emerged from Cooley Point and other related sites (e.g. McCabe *et al.*, 1984; 1994) suggests that there are at least five sequence stratigraphic elements which have widespread applicability to deglacierized basins elsewhere.

1. In large isostatically depressed basins, deglacial sequences show considerable lithofacies diversity as a result of an unsteady system subject to changes in ice marginal configuration and variations in r.s.l.

(England *et al.*, 1981; England, 1983; Powell, 1990; Shaw, 1994). More specifically, the Cooley Point sequence demonstrates that individual sites rarely record the full spectrum of facies formed during submergence and emergence. General models or event stratigraphies describing the nature of deglaciation should therefore be based on the greatest number of sites possible.

2. It is evident that the stratigraphic significance of surfaces of erosion or non-deposition or their correlative conformities associated with glacigenic sequences is generally overlooked. Although these surfaces may pass laterally into conformity or record truncation along metachronous depositional systems, they do provide information on changes in r.s.l. For example, in County Down, 10 km to the north of Cooley Point, channelled ravinement surfaces cut into glaciomarine deposits record a fall (~25 m) in r.s.l. or lowstand during the early late glacial (McCabe, 1986). Muds overlying the erosion surface record a rise in r.s.l. These sequences are truncated by a horizontal erosion surface which can be traced laterally into raised late glacial notches and beaches (correlative conformities). Both types of surface provide potential tools in the correlation of onshore and offshore sequences.
3. Glaciomarine muds around the margins of the Irish Sea Basin represent flooding zones as ice sheet margins contracted (Eyles and McCabe, 1989). These muds are important basinwide because they are dominated by cold water microfaunal elements, chiefly *Elphidium clavatum* (McCabe *et al.*, 1990). Similar living microfaunal frequencies have been recorded from recently deglacierized Arctic seas where they are considered to be opportunistic and related to cold (<1°C) turbid water close to glacier margins, shallow settings and low salinity water in areas of high sediment accumulation (Hald *et al.*, 1994). This shallow marine, benthic foraminiferal species in the Arctic seas provides a close analogy with the populations obtained from muds in the Irish Sea Basin. Common to both situations is the undoubted presence of major meltwater events during the deglacial cycle.
4. The boulder pavement at Cooley Point provides evidence for shore ice activity during the deglacial cycle. A variety of boulder beds, often one clast thick, have been recorded from glacigenic sequences in the Irish Sea Basin, though few detailed descriptions exist. Further work on their origins, especially their relationships with subjacent stratigraphies, may provide data either on r.s.l. changes or palaeoenvironmental settings.
5. Deformed, ice-marginal sediments, including muds, are frequently cited as evidence for ice advances or renewed ice marginal activity. Although the deformed gravel facies at Cooley Point is limited in scale, it indicates that shoreline ice processes operated near retreating ice margins. The geomorphic results are well known (Dionne, 1979). Within a large basin, subject to periods of catastrophic ice disintegration, breakup and meltwater events (e.g. Wingfield, 1989), ice floes may have played important roles in sediment deformation and compaction of glaciomarine sequences in shallow water. Dionne (1979) has demonstrated that intense ice pushing, facilitated by combinations of ice expansion and wind action, is particularly effective with daily and seasonal changes in water levels along an open water fetch. To date, work on deformed and compacted mud sequences exposed along the margins of the Irish Sea Basin rarely consider the effects of ice floes and shoreline ice processes.

In summary, the Cooley Point sequence records some of the sea level changes and deglacial history from the western sector of the Irish Sea Basin. The site records largely terrestrial submergence and preserves a well-formed intertidal boulder pavement within a deglacial sequence. Marine muds which underlie the pavement contain a low diversity, Arctic microfauna which is associated with a major meltwater event. Further work is necessary basinwide to investigate the full patterns of such events together with the sedimentological effects of sea ice activity. In a wider context, detailed facies analysis along emergent coasts provides an opportunity to investigate interactions between subaqueous, shoreline and glacigenic processes in the development of more accurate deglacial models.

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REFERENCES

Araya, R. and Hervé, F. 1972. 'Patterned gravel beaches in the South Shetland Islands', in Adie, R. J. (Ed.), *Antarctic Geology and Geophysics*, IUGS Series B, **1**, 111–114.

Boulton, G. S. 1978. 'Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis', *Sedimentology*, **25**, 773–799.

Boulton, G. S. 1990. 'Sedimentary and sea level changes during glacial cycles and their controls on glacimarine facies architecture', in Dowdeswell, J. A. and Scourse, J. D. (Eds), *Glacimarine Environments: Processes and Sediments*, Geological Society Special Publication No. **53**, 15–32.

Bowen, D. Q., Rose, J., McCabe, A. M. and Sutherland, D. G. 1986. 'Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales', *Quaternary Science Reviews*, **5**, 299–340.

Clark, P. U. 1991. 'Striated clast pavements: products of deforming subglacial sediment', *Geology*, **19**, 530–533.

Clark, P. U. and Hansel, A. K. 1989. 'Till lodgement, clast ploughing and glacier sliding over a deformable glacier bed', *Boreas*, **18**, 201–207

Dardis, G. F. and McCabe, A. M. 1983. 'Facies of subglacial channel sedimentation in late Pleistocene drumlins, Northern Ireland', *Boreas*, **12**, 263–278.

De Raaf, J. F. M., Boersma, J. R. and Van Gelder, A. 1977. 'Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland', *Sedimentology*, **24**, 451–483.

Dionne, J. C. 1979. 'Ice action in the lacustrine environment. A review with particular reference to subarctic Quebec, Canada', *Earth Science Reviews*, **15**, 185–212.

Dionne, J. C. 1981. 'A boulder-strewn tidal flat, north shore of the Gulf of St. Lawrence, Quebec', *Géographie physique et Quaternaire*, **35**, 261–267.

England, J. 1983. 'Isostatic adjustments in a full glacial sea', *Canadian Journal of Earth Sciences*, **20**, 895–917.

England, J., Bradley, R. S. and Stuckenrath, R. 1981. 'Multiple glaciations and marine transgressions, western Kennedy Channel, Northwest Territories, Canada', *Boreas*, **10**, 71–89.

Eyles, C. H. 1988. 'A model for striated boulder pavement formation on glaciated, shallow-marine shelves: an example from the Yakataga Formation, Alaska', *Journal of Sedimentary Petrology*, **58**, 62–71.

Eyles, C. H. 1994. 'Intertidal boulder pavements in the northeastern Gulf of Alaska and their geologic significance', *Sedimentary Geology*, **88**, 161–173.

Eyles, N. and McCabe, A. M. 1989. 'The Late Devensian (<22 000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin', *Quaternary Science Reviews*, **8**, 307–351.

Guilcher, A. 1981. 'Cryoplanation littorale et cordons glaciels de basse mer dans la région de Rimouski, Cote Sud de L'estuaire du Saint-Laurent, Québec', *Géographie physique et Quaternaire*, **35**, 155–169.

Gustavson, T. C. and Ashley, G. M. 1975. 'Depositional sequences in glaciolacustrine deltas', in Jopling, A. V. and McDonald, B. C. (Eds), *Glaciofluvial and Glaciolacustrine Sedimentation*, Society of Economic Palaeontologists and Mineralogists, Special Publication No. **23**, 264–280

Hald, M., Steinsand, P. I., Dokken, T., Korsun, S., Polyak, L. and Aspeli, R. 1994. *Recent and late Quaternary distribution of Elphidium Excavatum F. Clavatum in Arctic seas*, Cushman Foundation Special Publication No. **32**, 141–153.

Hansom, J. D. 1983. 'Ice-formed intertidal boulder pavements in the subantarctic', *Journal of Sedimentary Petrology*, **53**, 135–145.

Hansom, J. D. 1986. 'Intertidal forms produced by floating ice in Vestfirdir, Iceland', *Marine Geology*, **71**, 289–298.

Hicock, S. R. 1991. 'On subglacial stone pavements in till', *Journal of Geology*, **99**, 607–619.

Holland, C. H. 1981. *A Geology of Ireland*, Scottish Academic Press, Edinburgh, 335 pp.

Iseya, F. and Ikeda, H. 1987. 'Pulsations in bedload transport rates induced by a longitudinal sediment sorting: a flume study using sand and gravel mixtures', *Geografiska Annaler*, **69A**, 227–253.

Jennings, A. E. and Helgadottir, G. 1994. 'Foraminiferal assemblages from the Greenland fjords and shelf of eastern Greenland', *Journal of Foraminiferal Research*, **24**, 123–144.

Lauriol, B. and Gray, J. T. 1980. 'Processes responsible for the concentration of boulders in the intertidal zone in leaf basin, Ungava', in McCann, S. B. (Ed.), *The Coastline of Canada*, Geological Association of Canada, Paper **80-10**, 281–292.

Leffingwell, E. de K. 1919. *The Canning river region, northern Alaska*, United States Geological Survey Professional Paper **109**, 1–251.

Lowe, D. R. 1979. 'Sediment gravity flows: their classification and some problems of application to natural flows and deposits', in Doyle, L. R. and Pilkey, O. H. (Eds), *Geology of Continental Slopes*, Society of Economic Paleontologists and Mineralogists, Special Publication **27**, 75–82.

Lowe, D. R. and LoPiccolo, R. D. 1974. 'The characteristics and origins of dish and pillar structures', *Journal of Sedimentary Petrology*, **44**, 484–501.

Mackay, J. R. and Mackay, D. R. 1977. 'The stability of ice-push features, Mackenzie River, Canada', *Canadian Journal of Earth Science*, **14**, 2213–2225.

Martini, I. P. 1981. 'Ice effect on erosion and sedimentation on the Ontario shores of James Bay, Canada', *Zeitschrift für Geomorphologie*, **25**, 1–7.

McCabe, A. M. 1973. 'The glacial stratigraphy of eastern counties Meath and Louth', *Proceedings of the Royal Irish Academy*, **73B**, 355–382.

McCabe, A. M. 1986. 'Glaciomarine facies deposited by retreating tidewater glaciers—an example from the Late Pleistocene of Northern Ireland', *Journal of Sedimentary Petrology*, **56**, 880–894.

McCabe, A. M. and O'Cofaigh, C. 1995. 'Late Pleistocene morainal bank facies at Greystones, eastern Ireland: an example of sedimentation during ice marginal re-equilibrium in an isostatically depressed basin', *Sedimentology*, **42**, 647–663.

McCabe, A. M., Dardis. G. F. and Hanvey, P. M., 1984. 'Sedimentology of a Late-Pleistocene submarine-moraine complex, County Down, Northern Ireland,' *Journal of Sedimentary Petrology*, **54**, 716–730.

McCabe, A. M., Dardis, G. F. and Hanvey, P. M. 1987. 'Sedimentation at the margins of a late Pleistocene ice lobe terminating in shallow marine environments, Dundalk Bay, eastern Ireland', *Sedimentology*, **34**, 374–493.

McCabe, A. M., Eyles, N., Haynes, J. R. and Bowen, D. Q. 1990. 'Biofacies and sediments in an emergent Late Pleistocene glaciomarine sequence, Skerries, east central Ireland', *Marine Geology*, **94**, 23–36.

McCabe, A. M., Carter, R. W. G. and Haynes, J. R. 1994. 'A shallow marine emergent sequence from the northwestern sector of the last British ice sheet, Portballintrae, Northern Ireland', *Marine Geology*, **117**, 19–34.

McCann, S. B., Dale, J. E. and Hale, P. B. 1981. 'Subarctic tidal flats in areas of large tidal range, southern Baffin Island, eastern Canada', *Géographie physique et Quaternaire*, **35**, 183–204.

Nagy, J. 1965. 'Foraminifera in some bottom samples from shallow waters in Vestspitzbergen', Norsk Polarinstitútt Årbok 1963, 109–125.

Nemec, W. and Steel, R. J. 1984. 'Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass flow', in Koster, E. H. and Steel, R. J. (Eds), *Sedimentology of Gravels and Conglomerates*, Memoir Canadian Society of Petroleum Geologists, **10**, 1–31.

Nichols, R. L. 1961. 'Characteristics of beaches formed in polar climates', *American Journal of Science*, **259**, 694–708.

Postma, G. 1983. 'Water escape structures in the context of a depositional model of a mass flow dominated conglomeratic fan-delta (Abrioja Formation, Pliocene, Almeria Basin, SE Spain)', *Sedimentology*, **30**, 91–103.

Postma, G. 1984. 'Mass flow conglomerates in a submarine canyon, Abrioja fan-delta, Pliocene, southeast Spain', in Koster, E. H. and Steel, R. J. (Eds), *Sedimentology of Gravels and Conglomerates*, Memoir Canadian Society of Petroleum Geologists, **10**, 237–258.

Postma, G. 1985. 'Resedimented conglomerates in the bottomsets of Gilbert-type gravel deltas', *Journal of Sedimentary Petrology*, **55**, 874–885.

Powell, R. D. 1981. 'A model for sedimentation by tidewater glaciers', *Annals of Glaciology*, **2**, 129–137.

Powell, R. D. 1983. 'Glaciomarine sedimentation in Glacier bay, Alaska', in Molnia, B. F. (Ed.), *Glacial-Marine Sedimentation*, Plenum Press, New York, 185–232.

Powell, R. D. 1990. 'Glacimarine processes at grounding-line fans and their growth to ice-contact deltas', in Dowdeswell, J. A. and Scourse, J. D. (Eds), *Glacimarine Environments: Processes and Sediments*, Geological Society Special Publication **53**, 53–74.

Reimnitz, E., Barnes, P., Forgatsch, R. and Rodeick, G. 1972. 'Influence of grounding ice on the arctic shelf of Alaska', *Marine Geology*, **13**, 323–334.

Rosen, P. 1979. 'Boulder barricades in central Labrador', *Journal of Sedimentary Petrology*, **49**, 1113–1124.

Rust, B. R. 1977. 'Mass flow deposits in a Quaternary succession near Ottawa, Canada: diagnostic criteria for subaqueous outwash', *Canadian Journal of Earth Sciences*, **14**, 175–184.

Shaw, J. 1975. 'Sedimentary successions in Pleistocene ice-marginal lakes', in Jopling, A. V. and McDonald B. C. (Eds), *Glaciofluvial and Glaciolacustrine Sedimentation*, Society of Economic Paleontologists and Mineralogists, Special Publication No. **23**, 281–303.

Shaw, J. 1994. 'A qualitative view of sub-ice-sheet landscape evolution', *Progress in Physical Geography*, **18**, 2, 159–184.

Shaw, J. and Gorrell, G. A. 1991. 'Subglacially formed dunes within biomodal and graded gravel in the Trenton drumlin field, Ontario, Canada', *Géographie physique et Quaternaire*, **45**, 21–34.

Stephens, N. and McCabe, A. M. 1977. 'Late Pleistocene ice movements and patterns of late- and post-glacial shorelines on the coast of Ulster, Ireland', in Kidson, C. and Tooley, M. J. (Eds), *The Quaternary History of the Irish Sea*, Seel House Press, Liverpool, 179–198.

Synge, F. M. 1977. 'The coasts of Leinster, Ireland', in Kidson, C. and Tooley, M. J. (Eds), *The Quaternary History of the Irish Sea*, Seel House Press, Liverpool, 199–222.

Tanner, V. 1939. 'Om de blockrika strandgördlana vid Subarktiska oceankuster', *Förekomstätt og Uppkomst Terra*, **60**, 157–165.

Taylor, R. B. and McCann, S. B. 1983. 'Coastal depositional landforms in northern Canada', in Smith, D. E. and Dawson, A. G. (Eds), *Shorelines and Isostasy*, Institute of British Geographers, Special Publication **16**, 53–75.

Wingfield, R. T. R. 1989. 'Glacial incisions indicating middle and upper Pleistocene ice limits off Britain', *Terra Nova*, **1**, 538–548.